Driving factors for occupant-controlled space heating in residential buildings

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Abstract

Occupant behaviour has a large impact on the energy consumption of buildings, and therefore a better understanding can assist in many building-related applications, such as facility management, building performance simulation and occupant guidance.

As occupant space-heating operation has a significant influence on the energy consumption of residential buildings in winter, an investigation of drivers for this behaviour was undertaken and the result is expressed in this paper. From the analysis, 27 drivers have been evaluated in previous behavioural studies and at present none of them can be identified confidently as having no influence.

Following the identification of these key drivers, the modelling of occupant space-heating behaviour in traditional building performance simulation was reviewed and the result indicates that most of these factors are typically ignored when modelling space-heating operation in building performance simulation.

It is concluded that future behavioural studies into the drivers discussed in this paper are needed to gain a better understanding and quantification of the impact of these factors on building energy use.

Keywords: occupant behaviour; space heating drivers; energy consumption; residential buildings; building simulation.

1. Introduction

Occupant behaviour in buildings has a significant impact on energy use, especially in dwellings [1-6]. In the past several decades, studies have been carried out to identify the variation of energy use in residential buildings due to differences in occupants' behaviour [7-12]; the reported magnitude of this variation varies significantly and covers a range of 4% [8] to 26% [12]. The actual impact of occupant behaviour on energy use in a specific residential building depends on various factors, such as occupant engagement, building automation, thermal properties of the building (insulation, thermal mass) and climate conditions [2, 5, 8, 13, 14]. Quantifying this impact is challenging: both the method of measuring the influence of people on the thermal behaviour of actual buildings and the method of modelling and simulating this influence need to capture all relevant drivers. Previous studies in this area typically cover only a limited set of parameters, risking incomplete observation and simulation – for instance through a simplified and schematic representation of the occupants' operation of heating controls or window operations [15-22]. Such a simplified view is also problematic for any work that aims to change occupant behaviour in order to reduce building energy use: in such work, it is important to understand both the existing behaviour and the factors that cause this behaviour. These factors are referred to as 'drivers' in this paper, the same as Fabi et al. [23] who have used the same term for window opening behaviour.

This paper critically assesses the existing literature on the underlying drivers of occupant space-heating behaviour in residential buildings, which can be used to guide both monitoring and simulation studies (Section 2). The paper then focuses on building simulation, and reviews how occupant space-heating behaviour has been modelled in existing simulation studies. Two key aspects are explored:

(1) the range of values that have been used to define the heating setpoint value in building simulation; and,
(2) the dependence of the heating setpoint value on influencing factors, that is, how the value changes over time when the simulation condition changes.

2. Factors influencing occupant space-heating behaviour

Occupants typically heat their buildings to keep warm in winter. Their preferred indoor temperature, however, can differ substantially from person to person [24, 25]. In this section, the underlying factors influencing occupants' space-heating behaviour are discussed. These factors are classified as:

- environmental factors: outdoor climate and indoor relative humidity;
- building and system related factors: dwelling type, dwelling age, dwelling size, room type, house insulation, type of heating system, type of temperature control, and type of heating fuel;
- occupant related factors: occupant age, occupant gender, occupant culture/race, occupant education level, social grade, household size, family income, previous dwelling type, house ownership, thermal sensation, perceived indoor air quality (IAQ) and noise, and health; and,
- other factors: time of day, time of week, occupancy, heating price, and energy use awareness.

The literatures reviewed for this section all focus on studies of drivers of occupants' space-heating behaviour in residential buildings. The papers cited have been taken from 1) SCI impact journals, such as Energy and Buildings or Building and Environment, and 2) key conferences, such as the IBPSA Building Simulation Conference or the ECEEE and ACEEE Summer Study Conferences.

In actual buildings, many of these factors will be correlated. For example, house insulation, the type of heating system and type of temperature control may relate to dwelling age. However, this paper discusses the influence of the above factors on space heating one at a time, reporting on conclusions from existing studies as to whether the factor's influence is deemed to be significant or insignificant. The possible combined influences of factors are not presented, unless these combinations have been expressed explicitly in the literature.

2.1 Environmental factors

The impact of **outdoor climate** on space heating has been evaluated in many existing studies. Newman and Day [26] suggested that night-time winter temperature settings were strongly affected by outdoor climate conditions, supported by Pimbert and Fishman [27]. Additionally, both Vine [28] and French et al. [29] found that homes in warmer climates turned the heating system off or maintained lower winter settings than those located in colder climates. Based on a questionnaire survey, Andersen et al. [13] suggested that "*the proportion of dwellings with the heating turned on was strongly related to the outdoor temperature*", and this is supported by real-measured data from 13 Danish dwellings [30]. Besides outdoor temperature, outdoor humidity and the wind speed were also found to influence the heating setpoint in dwellings [30]. Day and Hitchings [31] stated that the weather forecast affected occupants' heating behaviour greatly, based on an in-depth qualitative survey of 21 British households.

Fabi et al. [3] reported that for occupants who frequently adjusted thermostat settings (more than 50 times within a six-month period), **indoor relative humidity** drove them to turn up thermostatic radiator valve (TRV) settings significantly.

2.2 Building and system related factors

Dwelling type is a factor that has been investigated in many studies. From data collected in the US, Vine [28] found that winter thermostat settings were lower among multi-family dwellings, compared with other types of dwellings. From a survey carried out in 2356 households, Tachibana [32] also found that residents of apartments and condominiums were more likely to turn off their heating systems, compared with those living in houses. Additionally, they also had a lower proportion of morning and evening temperatures at high degrees, and higher temperatures at night. Based on data collected from 600 Swedish households, Linden et al. [33] suggested that families residing in detached houses tended to adopt lower indoor temperatures than those living in apartments, in order to save energy. Shipworth et al. [34] carried out a year-round study in 358 British houses, and found that the heating operation hour was statistically dependent on dwelling type, and that the largest difference was between detached and mid-terraced houses. Yohanis and Mondol [35] also investigated this factor in a study carried out in 25 households in Northern Ireland. They found that the lowest average temperature in winter was in terraced houses and the highest was in semi-detached houses, and they reasoned that the lower temperature in terraced houses might be caused by lower occupancies in that type of house. From a survey performed in over 500 homes in the UK, Kane et al. [36] analysed the average temperature in several types of dwellings: detached, semi-detached, end-terrace, mid-terrace and flat. They reported that flats were the warmest and detached dwellings were the coldest, with a difference of 2°C. The DEFRA (Department for Environment, Food & Rural Affairs), UK, [37] carried out a survey regarding thermostat settings, in which people living in flats also reported higher settings than those living in detached houses.

The influence of **dwelling age** has been explored in some studies. Vine [28] suggested that dwelling age had no effect on winter thermostat settings. In a national survey carried out in the UK, however, Hunt and Gidman [38] found that older homes were colder than newer homes from 1000 houses, although the analysis was affected by the strong associations between dwelling age, occupant income and the possession of central heating. Santin et al. [8] also found a small negative correlation between local heating in the living room and the construction year. In 2005, French et al. [29] also investigated this factor in their study and found that older houses tended to be colder. However, confounding factors such as the retrofit of thermal insulation, the heating fuel and region, could also possibly contribute to this temperature difference, rather than occupants' heating patterns.

The factor of **dwelling size** has been investigated in only one study carried out by Vine [28] and no significant influence was identified.

Many studies have evaluated the correlation between space-heating behaviour and **room type**. Hunt and Gidman [38] reported that livings room typically had a higher mean temperature than kitchens and bedrooms. Summerfield et al. [39] also observed this difference in 15 'low-energy' dwellings in the UK. Conner and Lucas [24] found that occupants chose different temperatures for different parts of their houses, based on data collected from 400 single-families in the US. For example, living rooms were about 2°C higher than bedrooms and about 6°C higher than basements. Oreszczyn et al. [40] monitored indoor temperatures in 1604 dwellings in five urban areas in the UK, and found that the daytime living room temperature was 2°C higher (19.1°C vs. 17.1°C) than the night-time bedroom temperature. French et al. [29] found that living rooms were heated more often than other rooms, such as bedrooms, laundries, bathrooms and corridors, and this finding is confirmed by Isaacs et al. [41] and Santin and Itard [8]. Yohanis and Mondol [35] carried out a ranking of indoor temperatures in different rooms, in which living rooms were the warmest, followed by kitchens, bedrooms and halls.

The influence of **house insulation** on space-heating operation has been evaluated as well in previous studies. Verhallen and Raaij [12] suggested that well-insulated building façades led to a lower bedroom temperature at night and a lower home temperature whilst occupied in winter. However, Pimbert and Fishman [27] reported that, on average, the living room and bedroom temperatures of insulated houses were warmer than that of uninsulated houses, supported by Haas et al. [1] based on data collected from about 400 Austrian households, and Shipworth et al. [34]. The study undertaken by Weihl and Gladhart [42] also revealed that poor thermal integrity led to more frequent winter thermostat manipulation, attempting to keep the indoor temperature tolerable.

Some studies have analysed the **type of heating system** as a factor of heating operation in dwellings. Hunt and Gidman [38] reported that centrally-heated houses were about 3°C warmer than non-centrally heated houses. However, an inverse trend was observed in a study carried out in Belgrade, Serbia [43], due to the use of district heating. Additionally, Andersen et al. [13] reported that the presence of wood burning stoves had a large impact on the control of the heating.

The **type of temperature control** has been evaluated as a driver as well. Nevius and Pigg [44] did a case study on space heating and thermostat use in 299 houses in the US, and found that households with programmable thermostats were much less likely to keep their thermostats at a constant temperature and had steeper setbacks both at night and during the day when the room was unoccupied, when compared with those with manual thermostats. Additionally, households with programmable thermostats selected slightly higher settings during the day when the room was occupied. Haiad and Peterson [45] obtained similar results from a survey carried out in several climate zones in the US. Furthermore, programmable thermostats were found to have a lower percentage of being set to “off”. De Groot et al. [46] suggested that occupants with analogue thermostats tended to lower the temperature more often, when leaving their houses for a long time, compared with occupants with programmable thermostats. Guerra-Santin et al. [5] described the results from two field studies, one was carried out by the OTB (Onderzoeksinstituut Technische Bestuurskunde) Research Institute for Housing, Mobility and Urban Studies and another one was carried out by the Dutch Ministry of Housing, both in the Netherlands. The former one is called the OTB survey and the latter one is called the WoON (Woononderzoek Nederland) survey. In the OTB survey, programmable thermostats resulted in more hours of open radiators than manual thermostats or manual valves on radiators. In the WoON survey, it was observed that the type of temperature control affected the number of rooms with radiators turned on. From another study carried out by the Kwalitatieve Woning Registratie of the Ministry of Housing of the Netherlands, Guerra-Santin et al. [8] also suggested that the presence of thermostats influenced both temperature settings and the number of bedrooms heated. Tachibana [32] analysed this factor as well and concluded that more occupants with programmable thermostats (86%) applied temperature setback from evening to night-time than those with manual thermostats (66%). In the study undertaken by Shipworth et al. [34], homes with manual thermostats had a 0.6°C lower thermostat setting than those with thermostatic control. Additionally, households using timers had a 0.4 hours longer heating period than those using manual operation. Conner and Lucas [24] also observed that clock thermostats led to a 0.5°C lower temperature setting than manual thermostats.

Vine [28] has evaluated the influence of **type of heating fuel** on heating operation but no positive conclusion was obtained. French et al. [29], however, suggested that occupant space-heating behaviour was affected by the heating fuel, and that houses heated by solid fuel burners were warmer than those heated by free-standing, portable LPG (liquefied petroleum gas) heaters or portable electric heaters.

2.3 Occupant related factors

Generally, the required indoor temperature in winter correlates with **occupant age** [47], so age can be a driver of space-heating operation. Guerra-Santin and Itard [5] reported that the elderly seemed to prefer higher indoor temperature settings in both OTB and WoON surveys, supported by many other studies [8, 31, 40, 42, 48-52]. Liao and Chang [53] suggested that "*the aged rely more heavily on space heating energy as they become older*", based on data collected in the residential Energy Consumption Survey [54] carried out by the DOE (Department of Energy in the US) in 1993. Kane et al. [55] monitored internal temperatures of over 300 dwellings in the UK and also found that older occupants required higher living room temperatures. Kavgic et al. [43], however, observed an inverse trend that the mean temperatures for the living room and the bedroom were lower in dwellings with elderly occupants aged 65 or over, when compared with that in buildings with younger occupants. Children also required warmer temperatures than adults, as reported by van Raaij and Verhallen [51], Weihl and Gladhart [42], and Xu et al. [50]. Some researchers such as Vine

[28] and Isaacs et al. [56] suggested that age had no relationship with space-heating behaviour in dwellings.

Karjalainen [57] confirmed the influence of **occupant gender** on the space-heating usage in residential buildings, as he observed that females preferred a higher indoor temperature; yet males were found to use thermostats more actively, based on interviews with a total of 3094 respondents. This is supported by Andersen [52], based on his questionnaire survey carried out in Denmark.

The influence of **occupant culture/race** has been investigated in two existing studies. Vine [28] found that black households preferred to maintain higher temperatures in winter than white households, and Wilhite et al. [58] observed different heating use in Japan and Norway, with respect to both the number of rooms heated and operating temperature setbacks.

Two studies have explored the influence of **occupant education level**, but their conclusions appear to be conflicting. Guerra-Santin and Itard [5] reported that occupants with a higher education level had fewer hours at the highest chosen temperature settings, when compared with those with a lower education level. Vine [28], however, suggested that occupant education level had no relationship with space-heating behaviour.

The **social grade** of occupants has been suggested by the DEFRA [59] as an influencing factor of space-heating behaviour.

The influence of **household size** has been investigated in many studies. In the studies carried out by Guerra-Santin et al. [5] and Isaacs et al. [56], no relationship between household size and winter thermostat settings was observed. However, Conner and Lucas [24] found that household size affected the number of temperature setbacks; they reported a smaller number of setbacks for higher numbers of occupants, and this is supported by Weihl and Gladhart [42]. Oreszczyn [40] observed a higher temperature for larger households, and attributed this to incidental heat gain, as well as a greater need for heating throughout the building. Sardianou [49] reported that household size caused differences in oil consumption for space heating in Greek houses.

More heating leads to higher heating costs, so the effect of **family income** on heating behaviour has been evaluated in some previous studies. Some studies suggested that family income had no impact on occupants' space-heating behaviour [5, 28, 29, 56]. Newman and Day [26], however, found that poor people tended to use less energy for keeping warm in the winter, supported by Hunt and Gidman [38], and, Day and Hitchings [31]. Additionally, Weihl and Gladhart [42] found, from interviews, that occupants agreed that the economy affected their use of thermostats. Sardianou [49] also suggested that households' annual income affected the energy consumed for space heating.

Guerra-Santin and Itard [8] investigated the influence of **previous dwelling type** on space-heating behaviour in the current dwelling, and suggested that households that previously lived in a single-family dwelling were more likely to have the thermostat at the highest chosen setting for a longer time, when compared with those previously living in a multi-family dwelling.

The influence of **house ownership** has been evaluated in some previous studies. The DEFRA [59] suggested that private renters set a higher thermostat setting than other tenure groups, supported by Andersen [52]. Additionally, Rehdanz [60] suggested that occupants in rented accommodation preferred to spend more on heating, regardless of the energy source, building type and household characteristic, based on information collected from 12,000 households in Germany. In Vine's study [28], however, no consistent relationship was found between winter thermostat settings and house ownership.

The main purpose of using heating is to keep rooms thermally comfortable, so occupants' **thermal sensation** can be expected to be an important driver of space-heating behaviour. Andersen et al. [13], however, suggested that occupants' space-heating behaviour was not correlated strongly with their thermal sensation, although Weihl and Gladhart [42] stated that occupants did say that thermal comfort was a factor affecting their use of thermostats. DEFRA [59] also reported that occupants with central heating stated that they typically changed the temperature setting whenever it got too hot or too cold, although this had not been confirmed by real monitored data.

In the questionnaire survey carried out by Andersen et al. [13] in Denmark, the interaction between the **perceived air quality and noise level** was suggested as a significant factor influencing the proportion of the dwelling with the heating on.

From interviews, Weihl and Gladhart [42] suggested that **health** was an influencing factor of space-heating behaviour.

2.4 Other factors

The **time of day** has been evaluated as a factor of space-heating behaviour in many studies. Newman and Day [26] reported that occupants generally kept their homes at different temperatures during the day and at night, supported by Berglund et al. [61], and, Day and Hitchings [31]. Vine [28] also observed significantly different winter thermostat settings during different periods of the day, supported by Tachibana [32]. Occupants generally prefer to adjust their heating settings at particular time of day [24, 27, 35, 42].

The influence of **time of week**, either weekdays or weekends, has been evaluated in a few studies. Conner and Lucas [24] revealed that occupants typically turned up thermostat settings on weekend mornings, compared to weekday mornings. However, this is not supported by Merier et al. [62], who reported that 89% of the respondents in their study said that they rarely or never set different programs for weekend and weekdays.

Turning heating down or off when leaving a house or a room is an efficient way to save energy, so space heating operation can be dependent on the **occupancy** of the dwelling. Many studies have revealed this dependence, that occupants prefer to keep the heating system on at the highest settings when they are at home [5, 28, 35, 36, 42, 49, 61, 63].

The **heating price** determines the amount of money an occupant would pay for heating their homes. Andersen et al. [13] analysed this factor, but found no significant influence. However, when comparing space-heating use in two different countries, namely, Japan and Norway, Wilhite et al. [58] observed significant behavioural difference, and they suggested that this was possibly caused by different prices of heating in these countries. Day and Hitchings [31] also found that people changed their heating behaviour in response to fuel price increases.

Some studies have tried to demonstrate that if occupants' know how much energy they have used for heating, it may possibly increase their consciousness of saving energy, and hence affect their space-heating behaviour, and this factor is called **energy use awareness** in this paper. Newman and Day [26] found that families paying their own fuel bills directly were more likely to control their houses efficiently, by using thermostats or radiator valves. Linden et al. [33] observed that households having a direct feedback on their energy use for heating preferred a lower indoor temperature of about 2°C, when compared with those whose heating was included in a monthly rent. De Groot et al. [46] noted that participants who kept a record of their energy use preferred lower heating temperature setpoints. Vine [28], however, found no influence from energy use awareness on occupants' winter thermostat settings.

2.5 Summary of influencing factors

Table 1 summarises the literature search of the potential influencing factors of space heating operation in residential buildings. In total, 41 papers discussing underlying drivers for this behaviour have been found.

In Table 1, Columns 2 and 3 provide a series of numbers that establish the current research findings on each factor. Column 2 provides the number of papers that report a correlation between the factor and space-heating behaviour, and Column 3 indicates the number of papers that report no correlation between the factor and space-heating behaviour.

Table 1: Overview of literatures evaluating the influencing factors of occupant space-heating behaviour

Potential drivers	Does the driver influence occupant space-heating behaviour? No. of papers reporting a correlation	No. of papers reporting no correlation
01. Outdoor climate	7	0
02. Indoor relative humidity	1	0
03. Dwelling type	7	0
04. Dwelling age	3	1
05. Dwelling size	0	1
06. Room type	8	0
07. House insulation	5	0
08. Type of heating system	3	0
09. Type of temperature control	9	0
10. Type of heating fuel	1	1
11. Occupant age	14	2
12. Occupant gender	2	0
13. Occupant culture/race	2	0
14. Occupant education level	1	1
15. Social grade	1	0
16. Household size	4	2
17. Family income	5	4
18. Previous dwelling type	1	0
19. House ownership	3	1
20. Thermal sensation	2	1
21. Perceived IAQ and noise	1	0
22. Health	1	0
23. Time of day	9	0
24. Time of week	1	1
25. Occupancy	8	0
26. Heating price	2	1
27. Energy use awareness	3	1

From Table 1, it can be seen that within these papers, no less than 27 possible factors have been evaluated as drivers for space-heating behaviour, but with varying conclusions regarding their causal effect. Within these factors, some have been studied more frequently than others, and the verdict on the individual factors is quite varied. Although the number of existing studies on each factor varies, the following factors can be said to be unambiguously assumed to be influential on space-heating behaviour in residential buildings: outdoor climate, dwelling type, room type, house insulation, type of temperature control, occupant age, time of day and occupancy. For all these factors, the number of papers confirming a correlation is much higher (more than 3 studies) than the number of papers rejecting a correlation. The remaining factors can be classified into three categories: (1) the influence of that factor has been confirmed in a small number of existing studies and no papers reject its influence; this category includes indoor relative humidity, type of heating system, occupant gender, occupant culture/race, social grade, previous dwelling type, perceived IAQ and noise, and health; (2) the influence of that factor has been rejected in a small number of existing studies and no papers confirm the influence; this category only includes dwelling size; and (3) the influence of that factor has both been confirmed and rejected in nearly equal numbers of existing studies; this category includes dwelling age, type of heating fuel, heating price, energy use awareness, occupant education level, household size, family income, house ownership, thermal sensation and time of week. The factors belonging to these three categories still need further investigations to fully establish their influence. Therefore, at this time, it is not possible to exclude any of the 27 possible factors suggested from previous studies of occupants' space-heating behaviour.

3. Modelling occupant space-heating behaviour in simulation

Building performance simulation (BPS) is currently used by researchers and building designers to analyse building performance. It is based on a mathematical representation of the building's heat balance, solved in the computer, which includes (1) heat from internal resources (e.g. people and equipment); (2) heat from the heating system; (3) heat through ventilation and infiltration; (4) heat transmission through the building façade (e.g. external wall, roof, external window, external door and ground floor); (5) heat from solar gains through external windows; and (6) heat stored in or released from thermal mass. See Figure 1. The energy required to heat a building is dependent on the balance of these six heat flows.

In the past, BPS was used mainly to compare design scenarios with different building constructions and systems. In those cases, accurate modelling of occupants' operation of the building was less important, as long as occupant behaviour was represented by the same operational schedule in all design scenarios. In the last two decades, more accurate modelling of occupant behaviour in BPS, and especially their operation of windows, blinds and artificial lights, has gained a great deal of research attention, due to the significant influence of occupants' behaviour on the performance of buildings [64-67]. In the following part of this paper, the current status of modelling occupant space-heating behaviour in BPS is reviewed, mainly from two aspects: (1) the selection of the heating setpoint values; and (2) the dependence of the heating setpoint value on influencing factors. In Section 3.1, simulation work investigating the influence of occupants' behaviour (including space-heating behaviour) on energy consumption of residential buildings is reviewed, focusing on the above two aspects. Then in Section 3.2, the review result is summarised and compared with that obtained in Section 2.5.

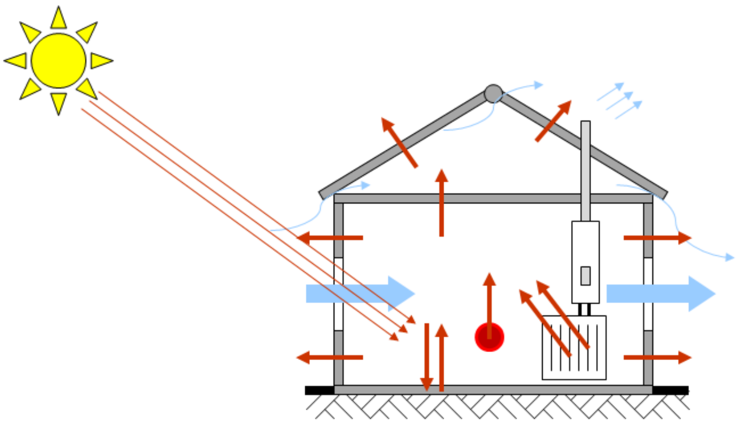

Figure 1: Heat balance within a building in winter

3.1 Examples of modelling space-heating behaviour in simulation

De Meester et al. [68] simulated the performance of a standard detached dwelling in Belgium, investigating the influence of three parameters related to the occupants' behaviour, on the dwelling’s heating loads: family size, operational time of the heating system and the area within a house to be heated. The building studied was a two-storey detached house, mainly facing southeast. In this simulation work, four heating-operation patterns deduced from real measurement in Belgian dwellings were used. Pattern 1 and Pattern 2 defined 20°C for occupied hours and 16°C for unoccupied hours and night-time. Pattern 3 kept the setting at 21°C constantly for the whole simulation period. Pattern 4 defined 24°C for the occupied hours and 20°C for unoccupied hours and night-time. Additionally, in this study, the heating was controlled specifically for various rooms on different floors of the building. Therefore, when modelling space-heating behaviour in this simulation work, influencing factors, namely, occupancy, room type and time of day, were considered.

Thomsen et al. [18] compared the simulated and real measured performance of 10 European houses, and used an indoor temperature of 20°C (typically presumed ideal or default value) for the entire simulation period. This temperature was also used by Tommerup et al. [16] to simulate the performance of five energy-efficient single-family bungalows, and Wall [17] to simulate the performance of 20 Swedish terrace houses. Additionally, Wall [69] changed the heating setpoint from 20°C to 26°C to evaluate the impact of changing behaviour on the building energy consumption. The ideal temperature of 20°C is also adopted as the internal setpoint temperature in winter by the ISO 13790 [70] and the energy certification proposal in Italy [71], for the estimation of building energy consumption.

Bojic et al. [72] used building performance simulation to analyse the impact of additional storey construction to the heating load of domestic buildings in Serbia. In their simulation work, different indoor design temperatures were assigned for different types of rooms, that is, 22°C for bathrooms; 20°C for living rooms, bedrooms and kitchens; and 15°C for hallways.

Love [73] evaluated the impact of changes in occupant space-heating behaviour on the energy use in current UK housing stocks. In her study, space-heating behaviour was represented by three factors, namely, heating temperature, space and time, according to field data collected in real buildings. For all behavioural aspects, three specific scenarios were defined, as shown in Table 2, and a behaviour change was achieved by jumping from one scenario to another. Therefore, in this study, influencing factors, namely, room type, time of day and possibly occupancy, were considered.

Table 2: Input values of variables in each behaviour scenario from Love [73]

Aspects	Low scenario	Middle scenario	High Scenario
Setpoint temperature	16°C	20°C	23°C
Number of rooms heated	Living room only	Living room, kitchen, bedrooms	All spaces
Daily heating periods	07:00-08:00 and 19:00-20:00	07:00-09:00 and 17:00-23:00	00:00-24:00

Branco et al. [74] studied the performance of a traditional multi-family building, which combined several renewable energy systems with an optimised envelope and electrical equipment. Based on three years of monitoring, they calculated the average temperature in the monitored apartments to be 22.5°C in the winter time, and used this value in their simulation work. Additionally, they also evaluated the building performance when the indoor temperature setting was chosen as 20°C, the ideal temperature indoors.

Saitoh and Fujino [75] did simulation work for an energy-efficient residential house in Japan and compared the simulation results with the monitored experimental data. In the simulation, they assumed the indoor temperature setting to be 23°C, with no explanation of where this value came from.

Karlsson et al. [22] compared the predicted energy use of a Swedish low-energy house during the design stage with its actual energy consumption after tenants moved in, and a difference of about 50% was observed. They suggested that one of the most important reasons for this huge difference was the lower temperature that was assumed in the simulation, which was between 23°C and 26°C, than that measured in the real house.

Blight and Coley [76] analysed the impact of a range of possible heating setpoints on the energy consumption of domestic buildings. In their study, the heating setpoint of thermostats were assumed to be constant for the whole heating period, but the values were chosen randomly from a normal distribution of preferred temperatures, which was obtained from real measured data. They reported that the mean normalised temperature of this distribution was 21.56°C with a standard deviation of 1.811°C.

Fabi et al. [3] classified building occupants into ‘passive users’, ‘medium users’, and ‘active users’, with respect to their frequency of adjusting the TRV settings in a 6-month period (March to August): 0-5 times for ‘passive users’; 6-50 times for ‘medium users’; more than 50 times for ‘active users’. They developed different space-heating behaviour models for these three types of heating users, with a consideration of the direction of TRV adjustment, that is, whether turning up or turning down. Table 3 listed the main factors used in their models, categorised by the type of heating users and the direction of TRV adjustment. In their study, the range of changeable heating setpoints was based on the comfort zone defined in the BS EN 15251 [77], that is from 18°C to 21°C.

Table 3: Influencing factors identified by Fabi et al. [3] to influence turning up/down of the heating system, for different user types

Direction / User type	Turning up	Turning down
Active TRV users	indoor relative humidity time of day outdoor temperature	solar radiation
Medium TRV users	outdoor temperature wind speed	time of day
Passive TRV users	N/A	wind speed

Wei et al. [78] used preference-based simulation to study behavioural change to save energy in residential buildings, through visualisation of the impact of changing behaviour on the house energy consumption. In their study, occupants were classified into three types, namely, 'active heating user (AHU)', 'medium heating user (MHU)' and 'passive heating user (PHU)'. However, unlike Fabi et al. [3], this classification was based on the preferred value of the heating setpoint rather than the number of times the heating setpoint was changed. For example, an AHU preferred a higher indoor temperature than a MHU or a PHU. Using simulation, they confirmed that an energy-efficient behaviour change could be achieved by changing from a more active user type to a more passive user type, that is either from an AHU to a MHU/PHU, or from a MHU to a PHU. The demonstration was carried out for an example room, and the preferred temperature setpoint was defined as 21°C for the AHU, 19.5°C for the MHU and 18°C for the PHU, also based on the range of comfort zone defined for living spaces in BS EN 15251 [77].

3.2 Summary of modelling space-heating behaviour in simulation

According to the above examples, there is still no standard method to assign the heating setpoint for building simulation. In previous studies, however, the value of the heating setpoint was mainly chosen by two methods:

- using assumed temperature either coming from the comfort zone defined in building standards [3, 78] or from researchers' experience/preference where an ideal temperature of 20°C was adopted popularly [17, 18, 70, 71, 74, 75]; and,
- using the measured temperature in actual buildings [68, 73, 79].

Although the latter method can help to improve the prediction results by eliminating the difference between the measured temperature and the assumed temperature, this method also has some weakness: (1) "*measured values shall be used with care, because the measured internal temperature is not the same as set-point due to effects such as overheating, intermittency, inertia, imperfect control*" [70]; and (2) it normally requires longitudinal monitoring of house temperature/thermostat settings for a significant period of time, and this is not applicable for general building design projects.

Figure 2 depicts the schematic process of BPS. It consists of the definition of a virtual experiment, the production of simulation output in terms of observable states, and finally post-processing or aggregation of these observable states into performance indicator values, following the structure presented by Augenbroe in [80]. In this process, modelling of occupant behaviour, such as space-heating behaviour and window opening behaviour, is a very important input of defining the operational conditions of a building.

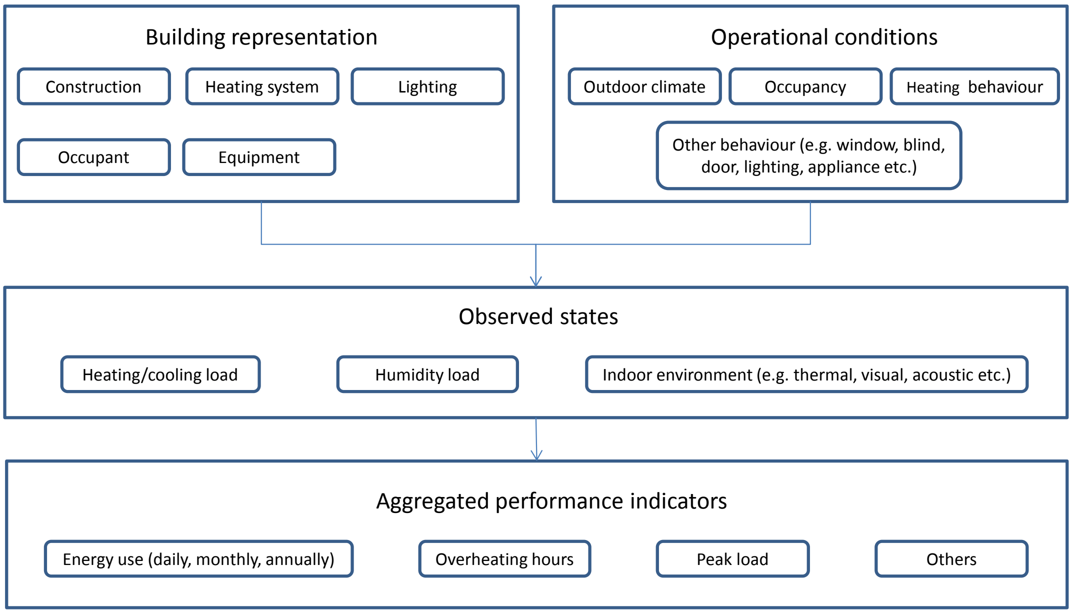

Figure 2: The schematic process of building performance simulation

As discussed in Table 1, existing studies have suggested 27 factors that influence occupants' space-heating behaviour. Therefore, it is important to discuss how these factors are being treated currently in BPS, especially when modelling space-heating behaviour. Figure 3 zooms in on the inputs of BPS (the top layer of the schematic process) and shows the available links between the 27 factors and each input category. According to the studies reviewed in Section 3.1, some factors discussed have been used to model space-heating behaviour in BPS, as enclosed by the dotted box. However, they include only a very small proportion of the factors (5 of 27). Meanwhile, there are many other factors being used for the modelling of other input categories in BPS, rather than space-heating behaviour. These factors are enclosed by the dashed box and the dotted box. The remaining 10 factors listed at the bottom of Figure 3, however, at present are ignored typically in the BPS.

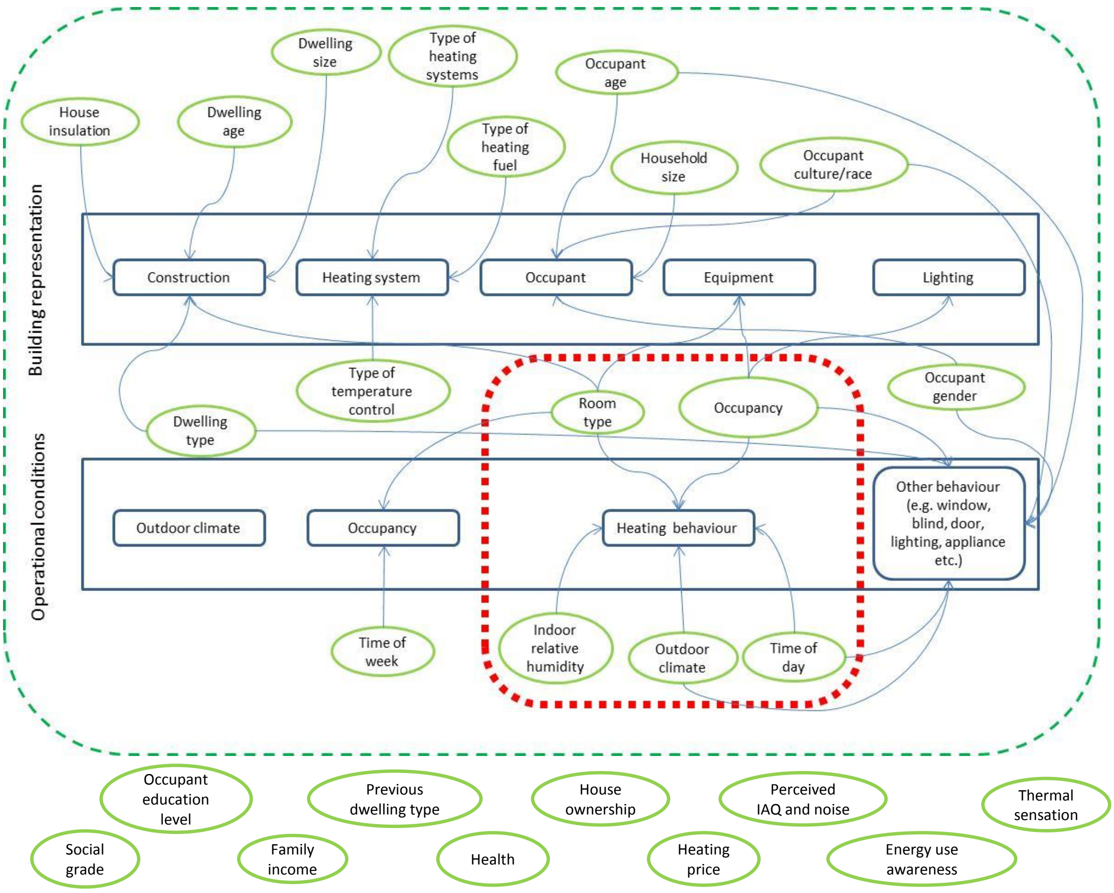

Figure 3: Links between influencing factors and BPS inputs

4. Conclusion

This paper highlights the complexity of occupants' space-heating behaviour in residential buildings: 27 factors that influence this behaviour have been suggested in previous studies. Some factors, such as outdoor temperature and dwelling type, have been evaluated in many studies and their influence on space heating seems to be well accepted. However, there are a number of factors, such as heating price and social grade, which have only been investigated in a limited number of studies and should be explored further. Based on the current body of knowledge, none of these factors can be identified confidently as having no influence on space-heating behaviour.

In building performance simulation, occupants’ space-heating behaviour is represented commonly by typical operational schedules, and only a few of those 27 influencing factors have been considered in the definition of these schedules. The involvement of all 27 influencing factors when modelling space heating in BPS should be able to help increase the simulation accuracy, but it also requires more information and time for the simulation work. Researchers have suggested that the accuracy of modelling/simulation should be dependent on the requirement of the simulation task [80, 81], and achieve a balance between the modelling accuracy with other items (for example, resources and time) within a simulation task. A possible solution for this is to consider the main factors in the simulation and then suitably discuss the influence of other factors on the simulation result.

It is concluded that future behavioural studies into the drivers discussed in this paper are needed to gain a better understanding and quantification of the impact of these factors on building energy use.

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